Heavy Quarks & PDFs

Fred Olness

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Conspirators:
P. Nadolsky, K. Park, M. Guzzi
I Schienbein, J.-Y. Yu,
K. Kovarik, T.P. Stavreva,
J. Owens, J. Morfin, C. Keppel, D. Soper ...

Loopfest
23 June 2010

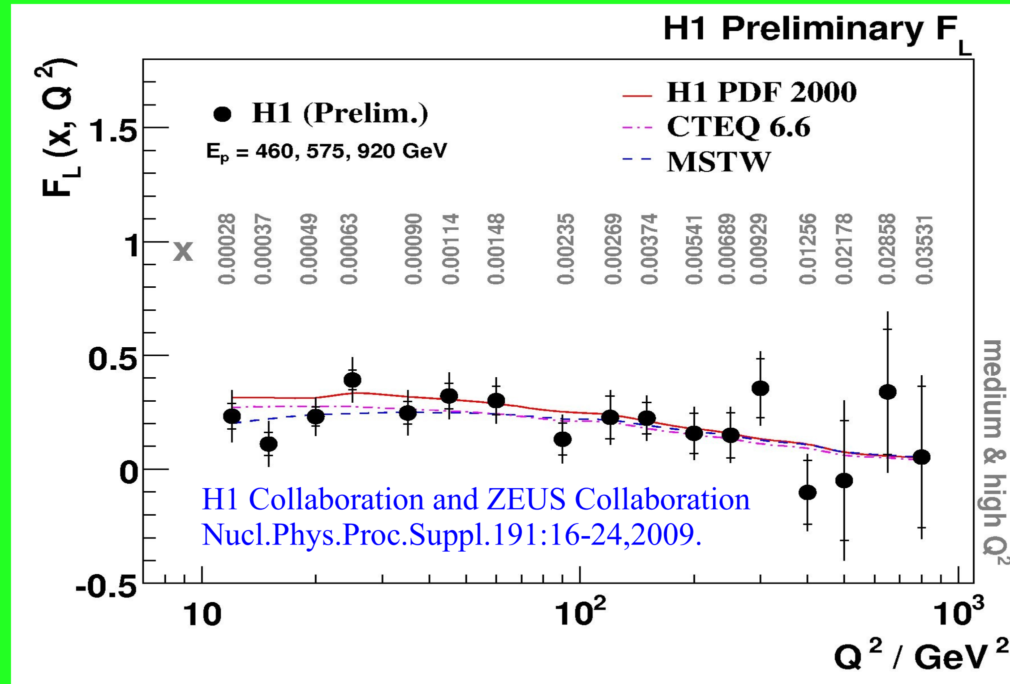
Motivation: Heavy Quarks and the multi-scale problem

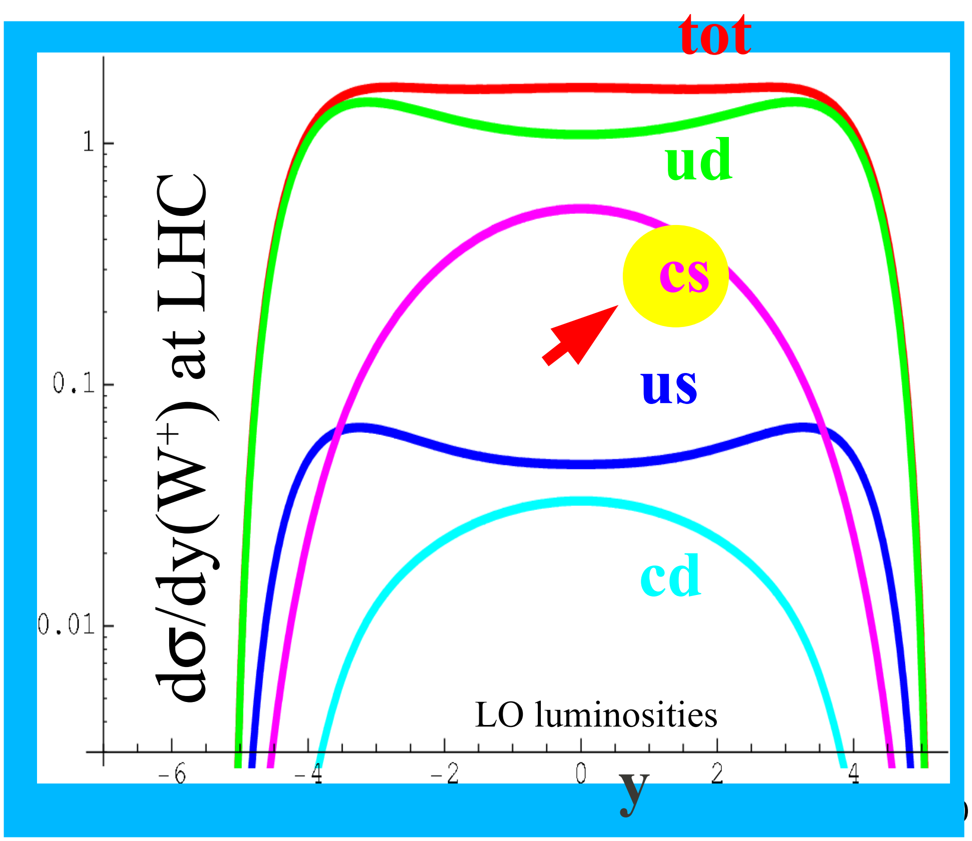
Two examples why heavy quarks are important

Mass terms can be leading effect

$$F_L \sim \frac{m^2}{Q^2}\; q(x) + \alpha_S\{\ldots\}$$

Masses are important





"Heavy Quarks" play a prominent role at the LHC

... heavy is a relative term

Two scale problem

Good News

GOOD NEWS: We have multiple schemes for heavy quark calculation

We have made progress in addressing how to compute heavy quarks. Recent efforts by many groups

The Cast:

ACOT & S-ACOT Codes
Used in CTEQ4HQ, 5HQ, 6HQ

Aivazis, Collins, Olness, Tung,
Phys.Rev.D50:3102-3118,1994.

S-ACOT
CTEQ 6.5 & 6.6

Tung, Lai, Belyaev, Pumplin, Stump, Yuan,
JHEP 0702:053,2007.
Nadolsky, Tung, Phys.Rev.D79:113014,2009.

Thorne-Roberts (TR')
MSTW Fits

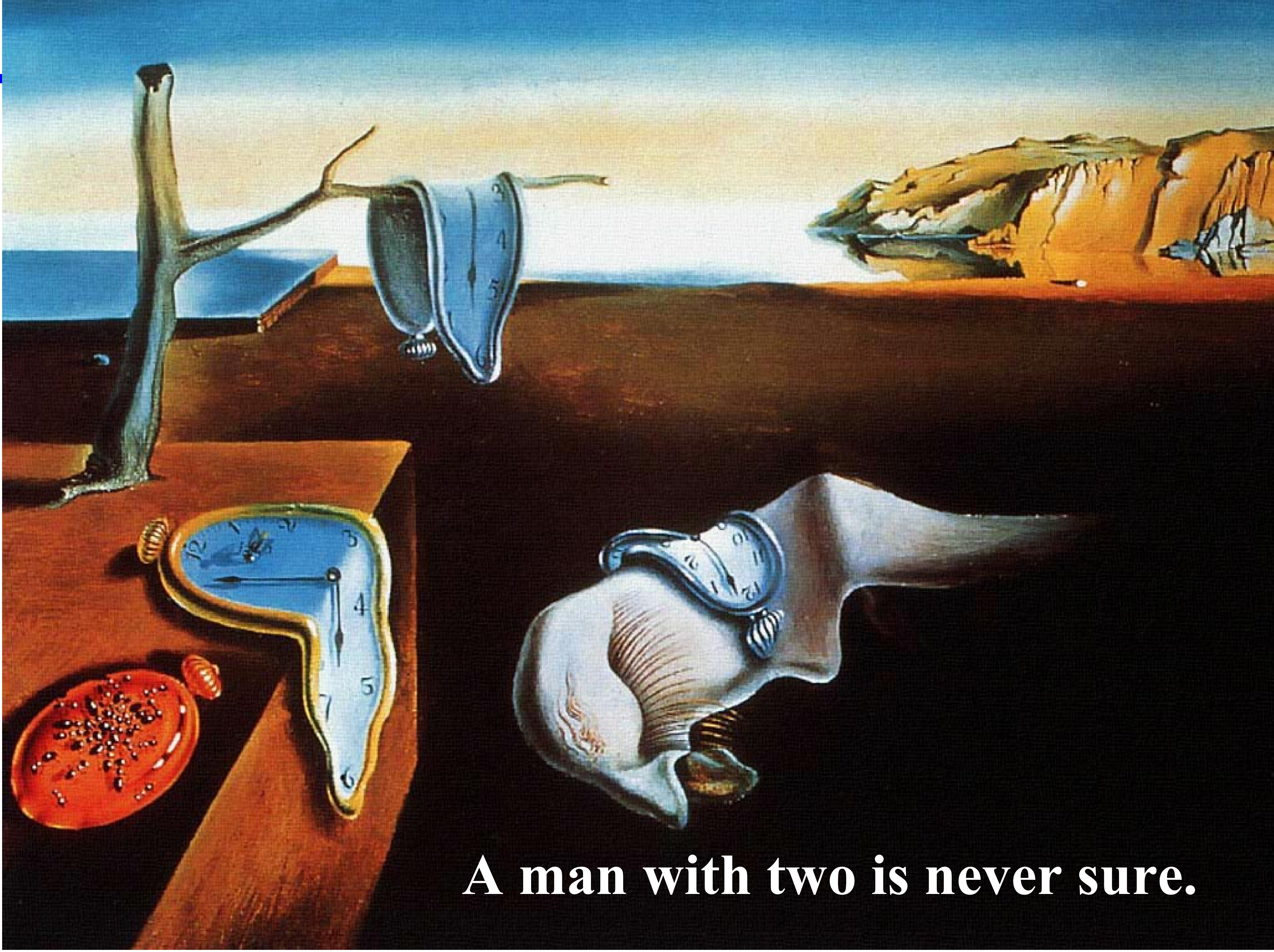
Thorne, Phys.Rev.D73:054019,2006.

FONLL:
Used in NNPDF Fits

Forte, Laenen, Nason, Rojo,
Nucl.Phys.B834:116-162,2010.

BUT: We have multiple schemes for heavy quark calculation

A man with one watch
knows what time it is ...


A man with two is never sure.

2009 Les Houches Comparative Studies

The SM and NLO Multileg Working Group: Summary report.

e-Print: arXiv:1003.1241 [hep-ph]

TeV 2009

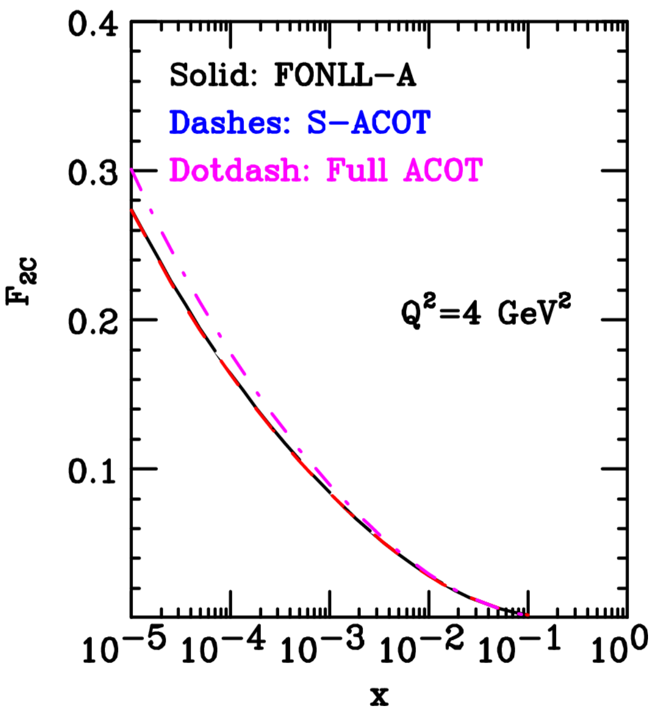
Physics at TeV Colliders

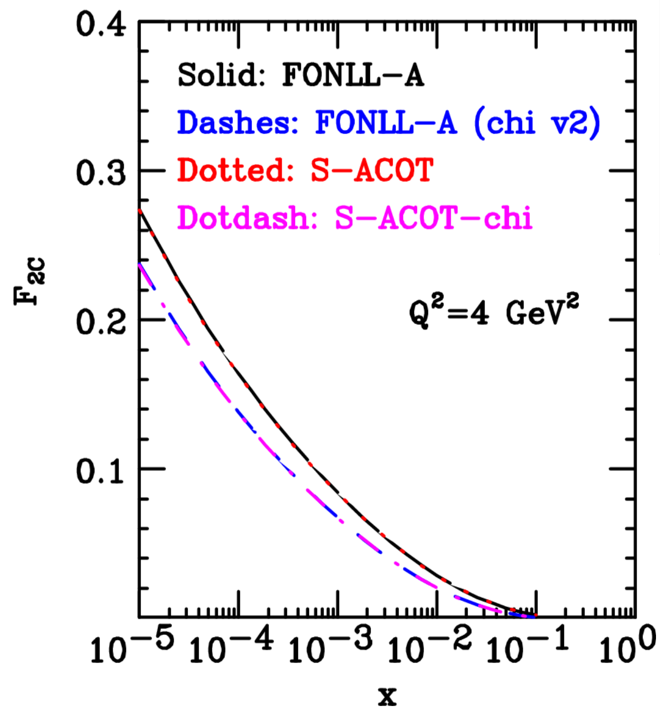
Les Houches 8-26 June 2009

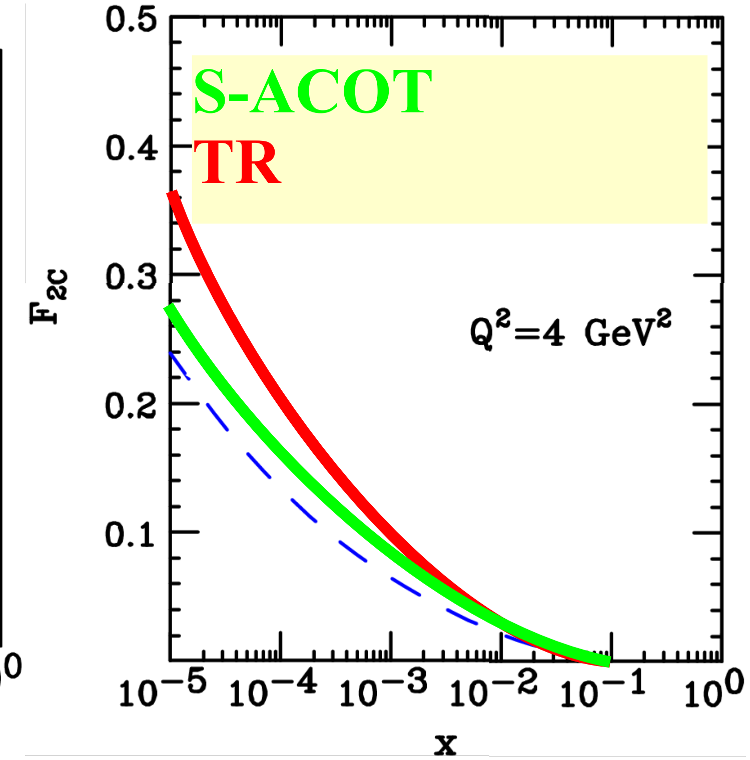
LES HOUCHES

centre de physique

Les Houches Comparative Study







ACOT & S-ACOT essentially identical

... scheme differences are higher order

FONNL & S-ACOT

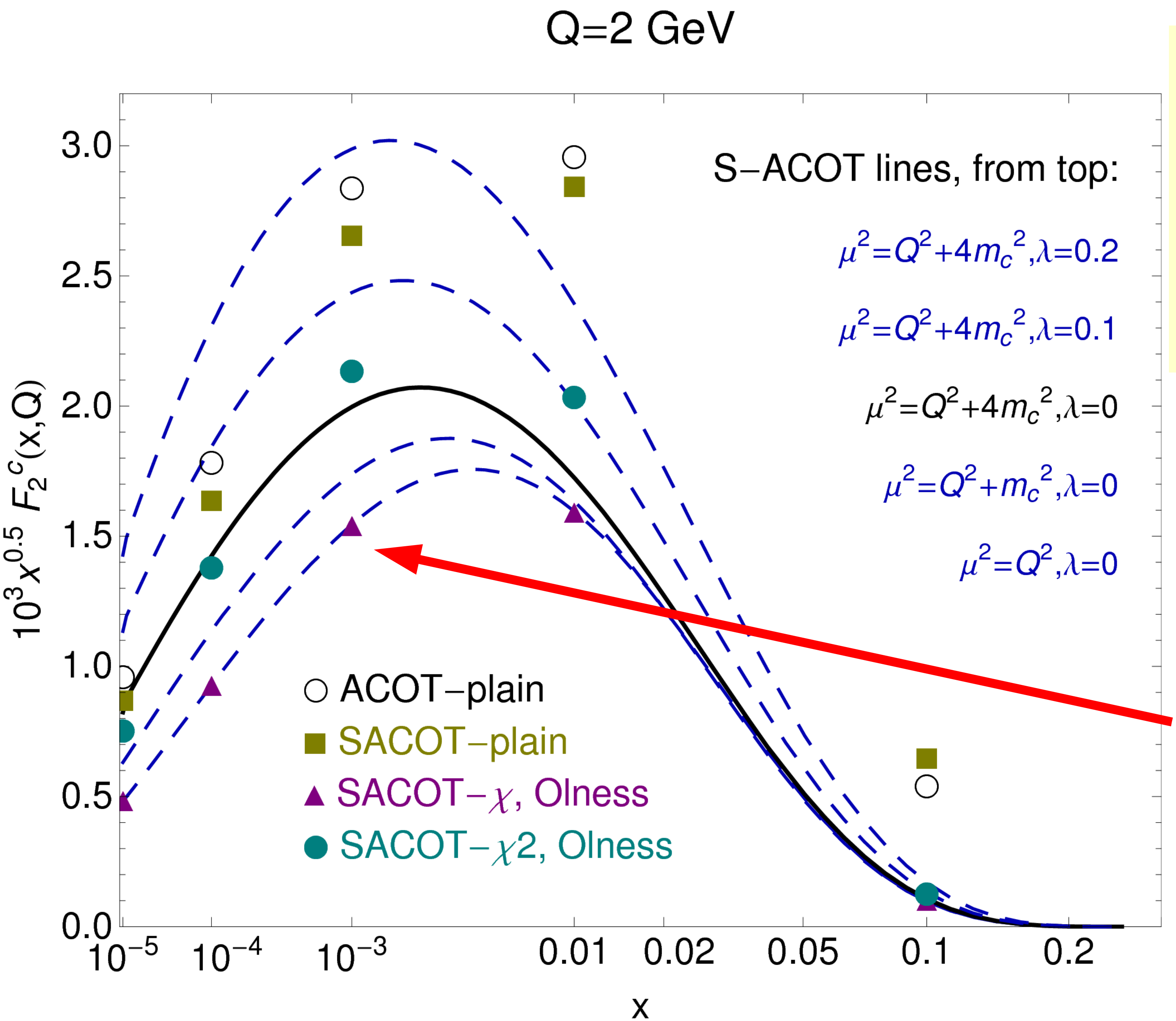
Numerically similar

MSTW09

We can quantify <u>theoretical</u> scheme diffferences

The SM and NLO Multileg Working Group: Summary report.
J. Rojo, et al., e-Print: arXiv:1003.1241 [hep-ph]

Comparison of ACOT code with Nadolsky/Tung



ACOT code

&

Nadolsky/Tung

Results check

$$x=\zeta(1+\zeta^{\lambda}\, m^2/Q^2)^{-1}$$

The Short Story:

S-ACOT implemetation matches

S-ACOT
CTEQ 6.5 & 6.6

Tung, Lai, Belyaev, Pumplin, Stump, Yuan,
JHEP 0702:053,2007.
Nadolsky, Tung, Phys.Rev.D79:113014,2009.

ACOT & S-ACOT Codes
Used in CTEQ4HQ, 5HQ, 6HQ

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S-ACOT & TR'
Separate schemes

S-ACOT & FONLL-A similar

FONLL:
Used in NNPDF Fits

Forte, Laenen, Nason, Rojo,
Nucl.Phys.B834:116-162,2010.

TR' & FONLL-C similar

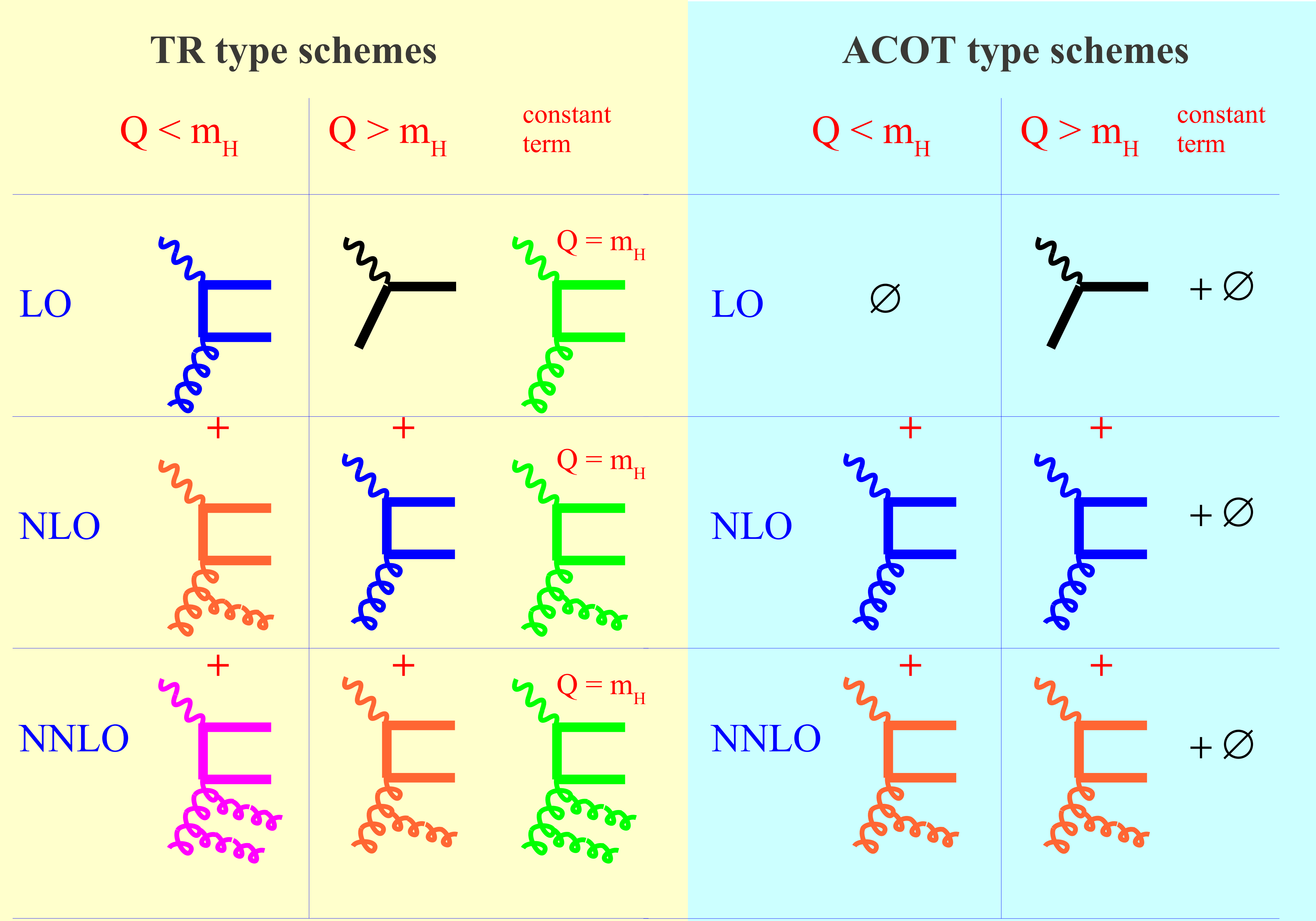
Thorne-Roberts (TR')
MSTW Fits

Thorne, Phys.Rev.D73:054019,2006.

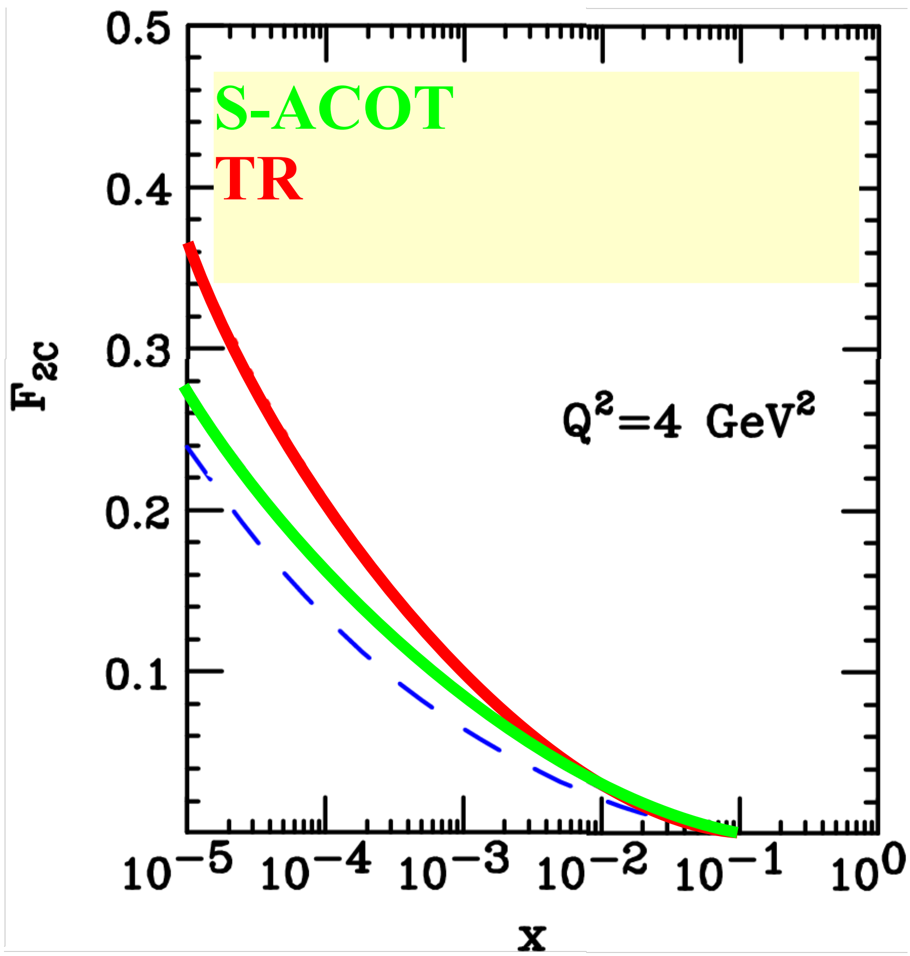
Compare & Contrast

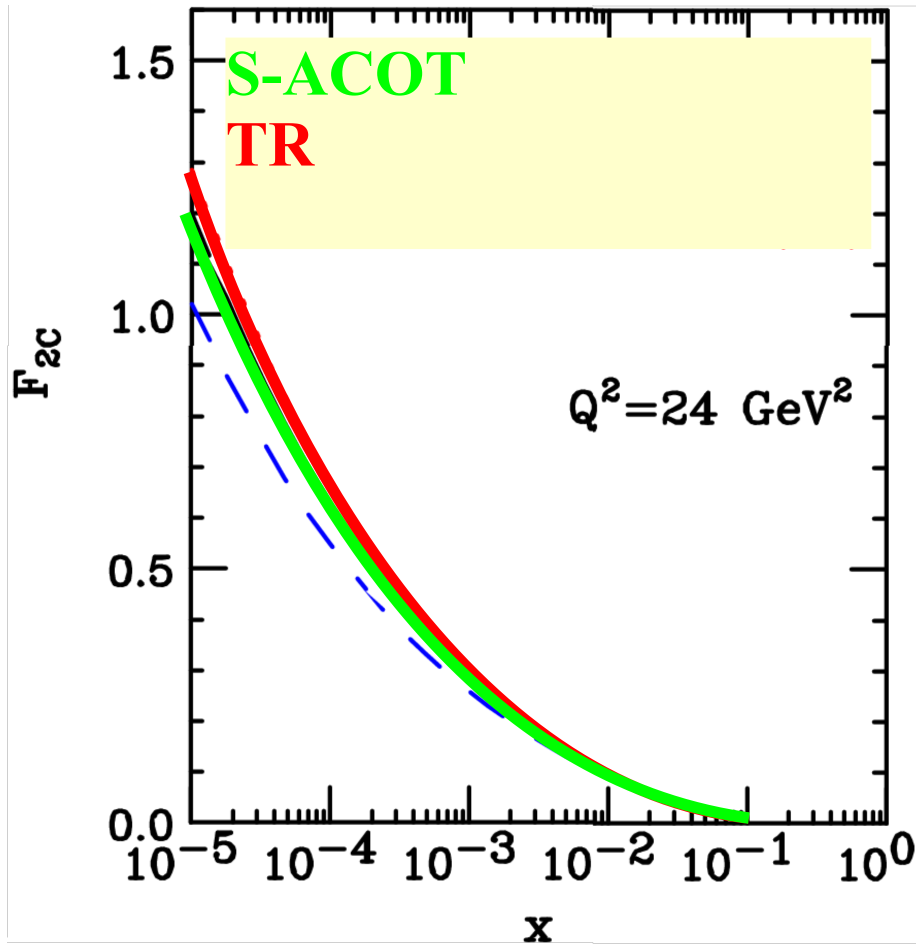
ACOT & TR

Schematic Summary of ACOT & TR Schemes



Comparison of ACOT & TR Schemes





Different schemes ⇒ Different PDFs ⇒ yet consistent σ

Differences reduce at:

1) higher Q,
2) higher order

If experiments are sensitive, time to compute to higher order

ACOT Features

ACOT: $m \to 0$ limit yields MS-Bar

with no finite renormalization

Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme

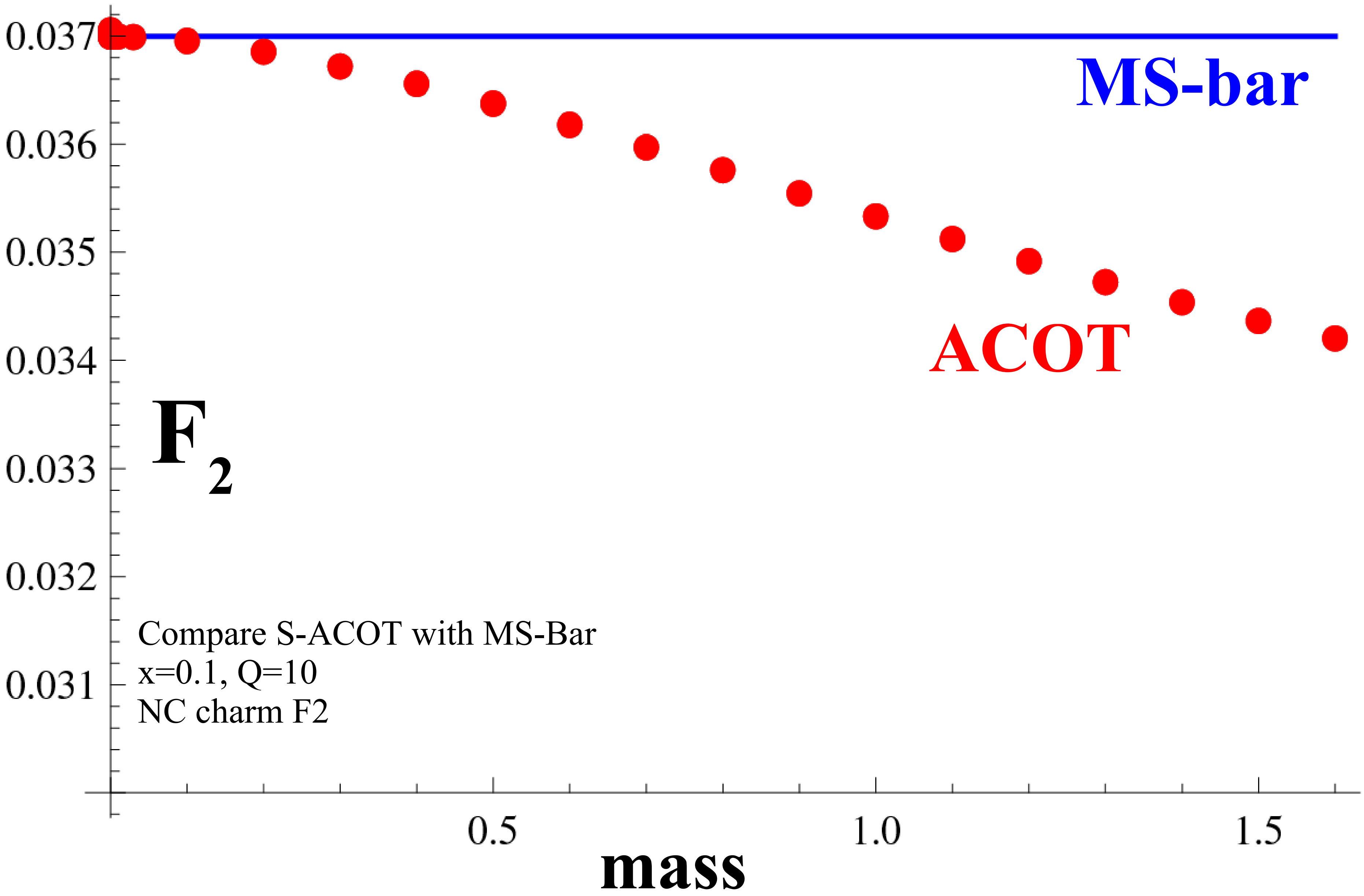
... hence, extensible to all orders

DGLAP kernels & PDF evolution are pure MS-Bar

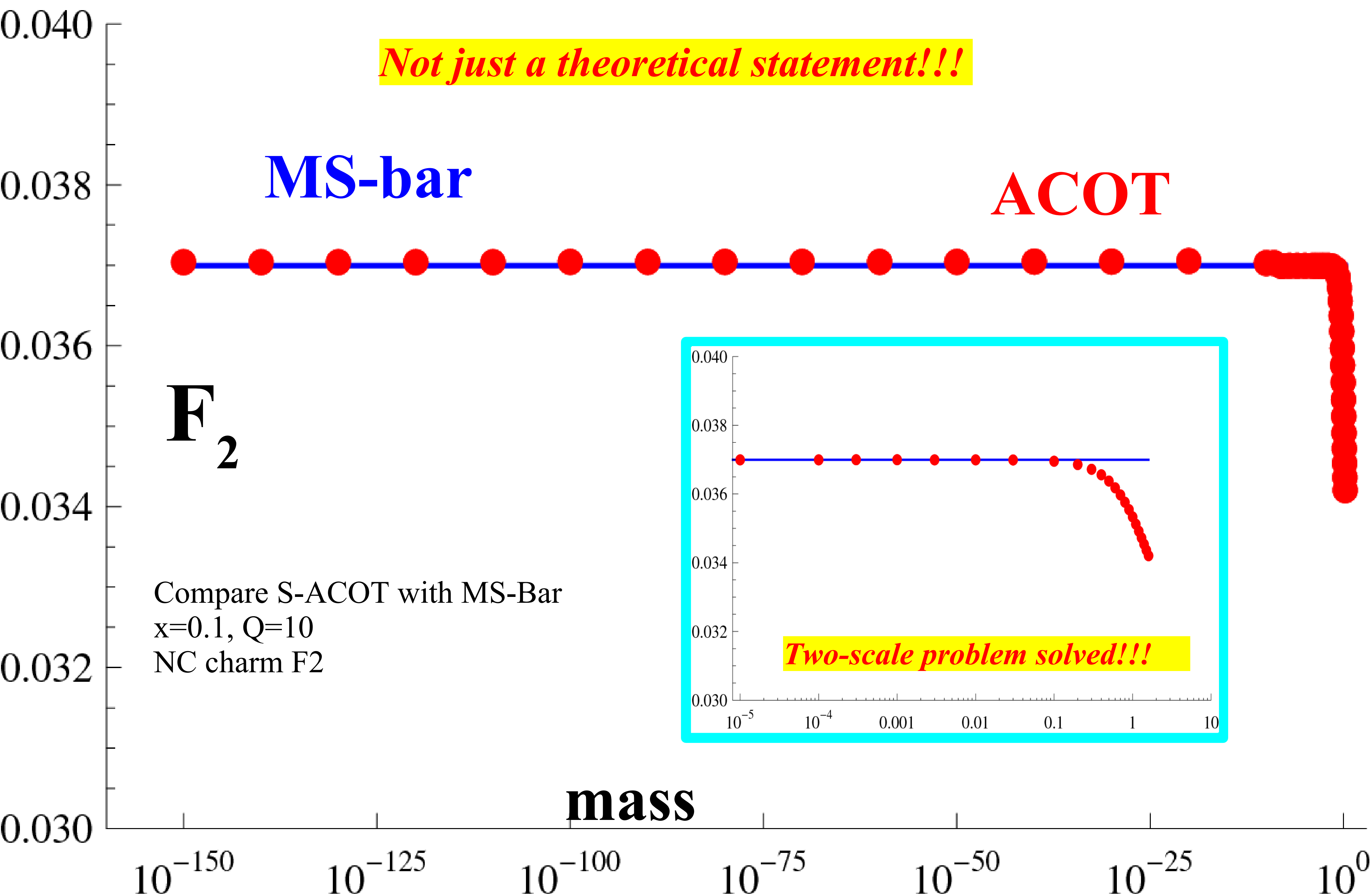
Definition of Subtractions analogous to MS-Bar

The minimal extension of MS-Bar scheme

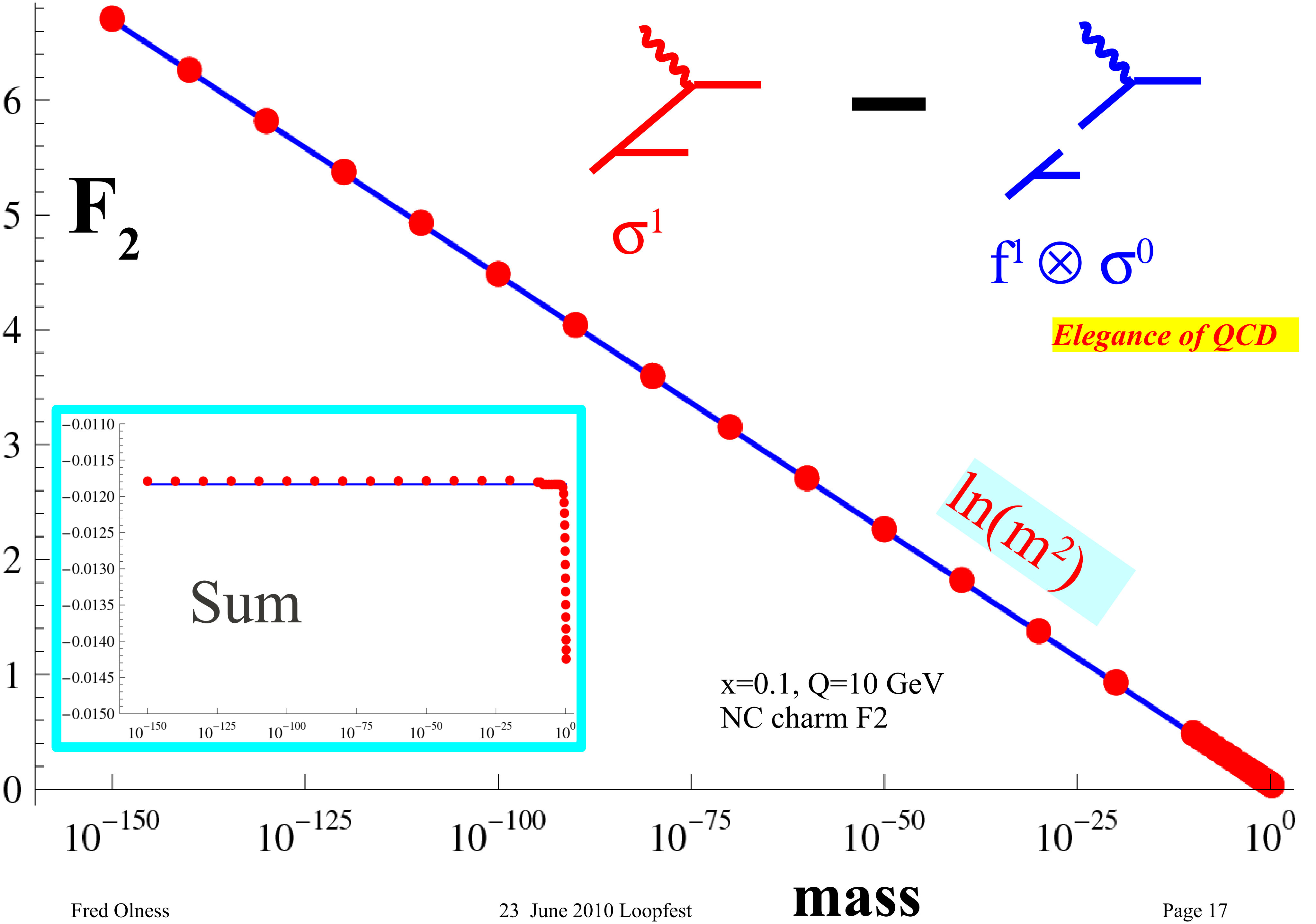
ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



Application of Factorization Formula at Leading Order (LO)

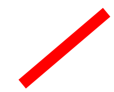
Basic Factorization Formula

$$\sigma = f \otimes \omega \otimes d + \mathcal{O}(\Lambda^2/Q^2)$$

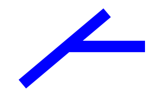
Note: not m^2/Q^2

At Zeroth Order:

$$\sigma^0 = f^0 \otimes \omega^0 \otimes d^0 \; + O(\Lambda^2/Q^2)$$



f^0



f^1

for parton target

Use: $f^0 = \delta$ and $d^0 = \delta$ for a parton target.

Therefore:

$$\sigma^0 = f^0 \otimes \omega^0 \otimes d^0 = \delta \otimes \omega^0 \otimes \delta = \omega^0$$

$$\boxed{\sigma^0 = \omega^0}$$

Z massive projection operators
Collins (1998)

Warning: *This trivial result leads to many misconceptions at higher orders*

Basic Factorization Formula

$$\sigma = f \otimes \omega \otimes d + \mathcal{O}(\Lambda^2/Q^2)$$

At NLO:

$$\sigma^1 = f^1 \otimes \omega^0 \otimes d^0 + f^0 \otimes \omega^1 \otimes d^0 + f^0 \otimes \omega^0 \otimes d^1$$

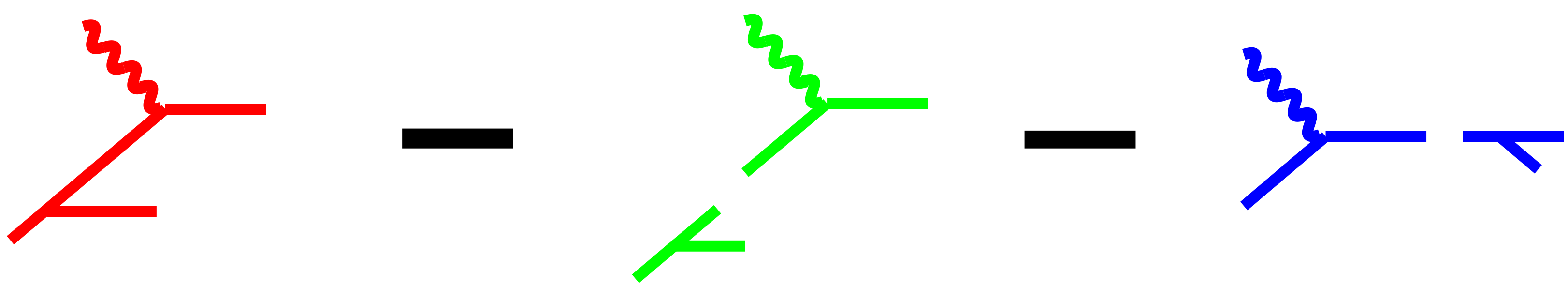
$$\sigma^1 = \quad f^1 \otimes \sigma^0 + \omega^1 + \sigma^0 \otimes d^1$$

f^0 f^1

We used: $f^0 = \delta$ and $d^0 = \delta$ for a parton target.

Therefore:

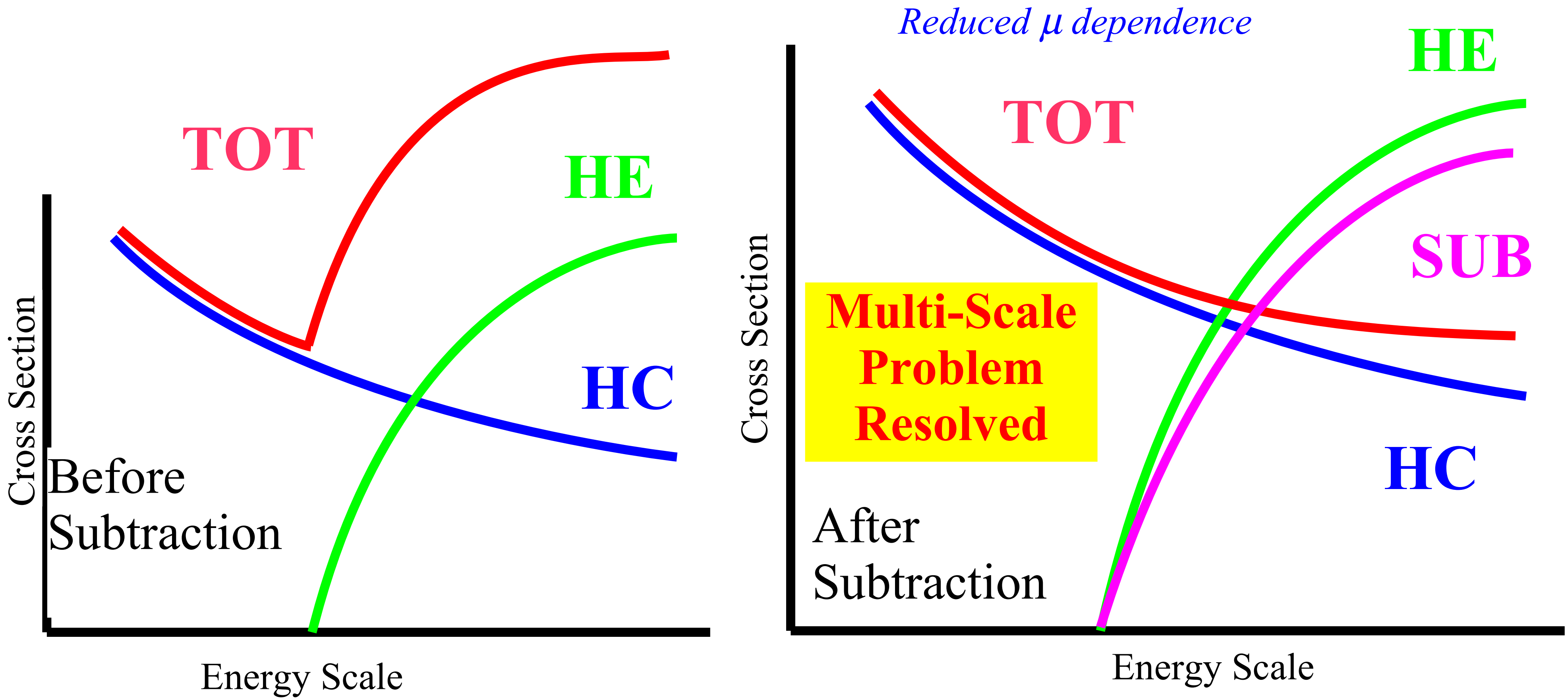
$$\omega^1 = \sigma^1 - f^1 \otimes \sigma^0 - \sigma^0 \otimes d^1$$

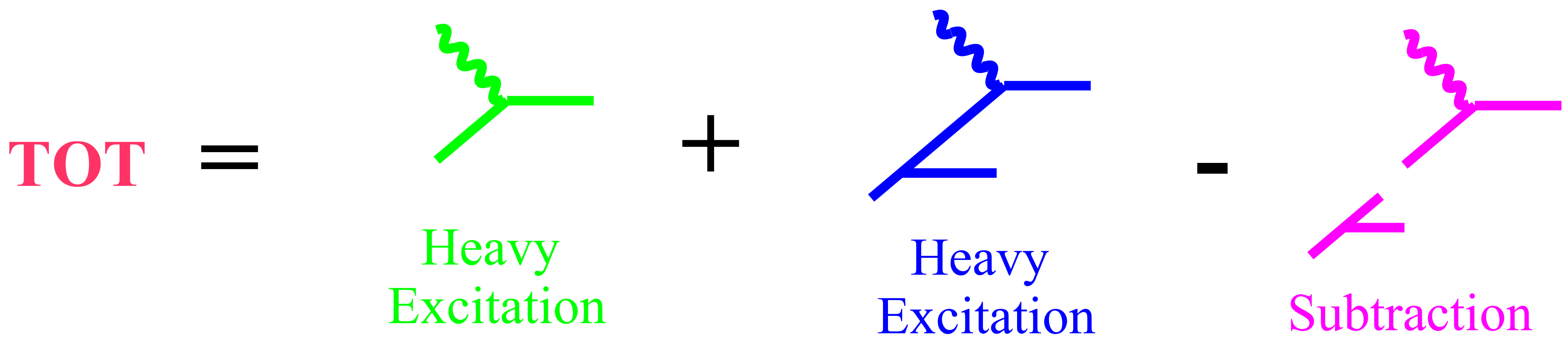


σ^1 $f^1 \otimes \sigma^0$ $\sigma^0 \otimes d^1$

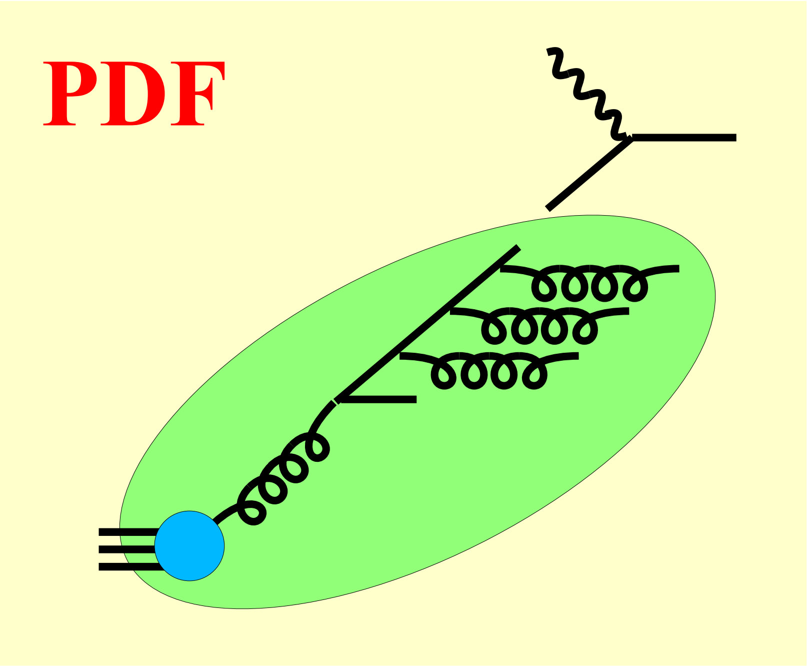
Z massive projection operators
Collins (1998)

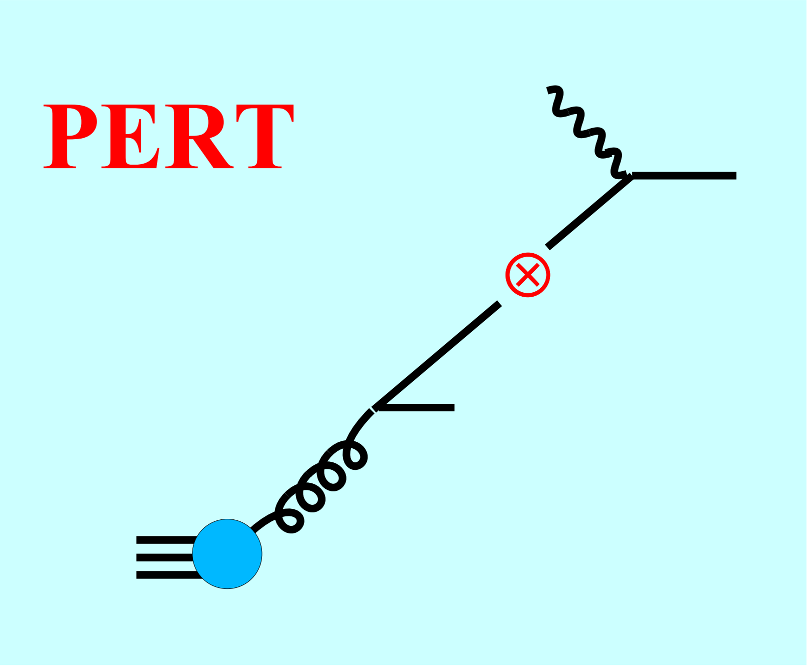
Interaction of the separate contributions vs. energy scale

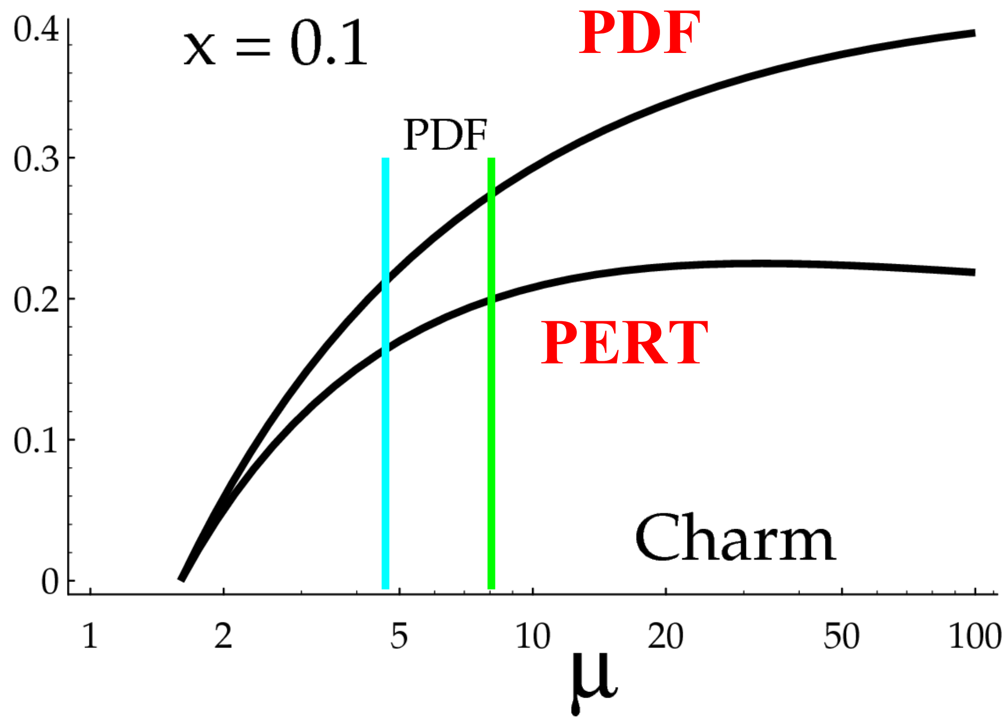




Rule of Thumb: When do we need to consider heavy quark PDF???







MORAL: You don't have to choose which expansion point you use;

by using the Heavy Quark PDF,
QCD will compensate

In practice ...

Using the heavy quark PDF's we can accommodate quark masses of any values: e.g., 10^{-150} to 10^{+150}

In general, applicable to all schemes

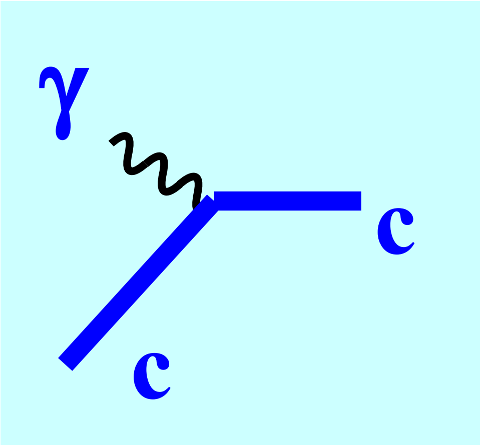
χ scaling

χ-Scaling: Effect of Kinematic Mass Re-Scaling

ACOT (Aivazis, Collins, Olness, Tung) A general framework for including the heavy quark components.
Phys.Rev.D50:3102-3118,1994.

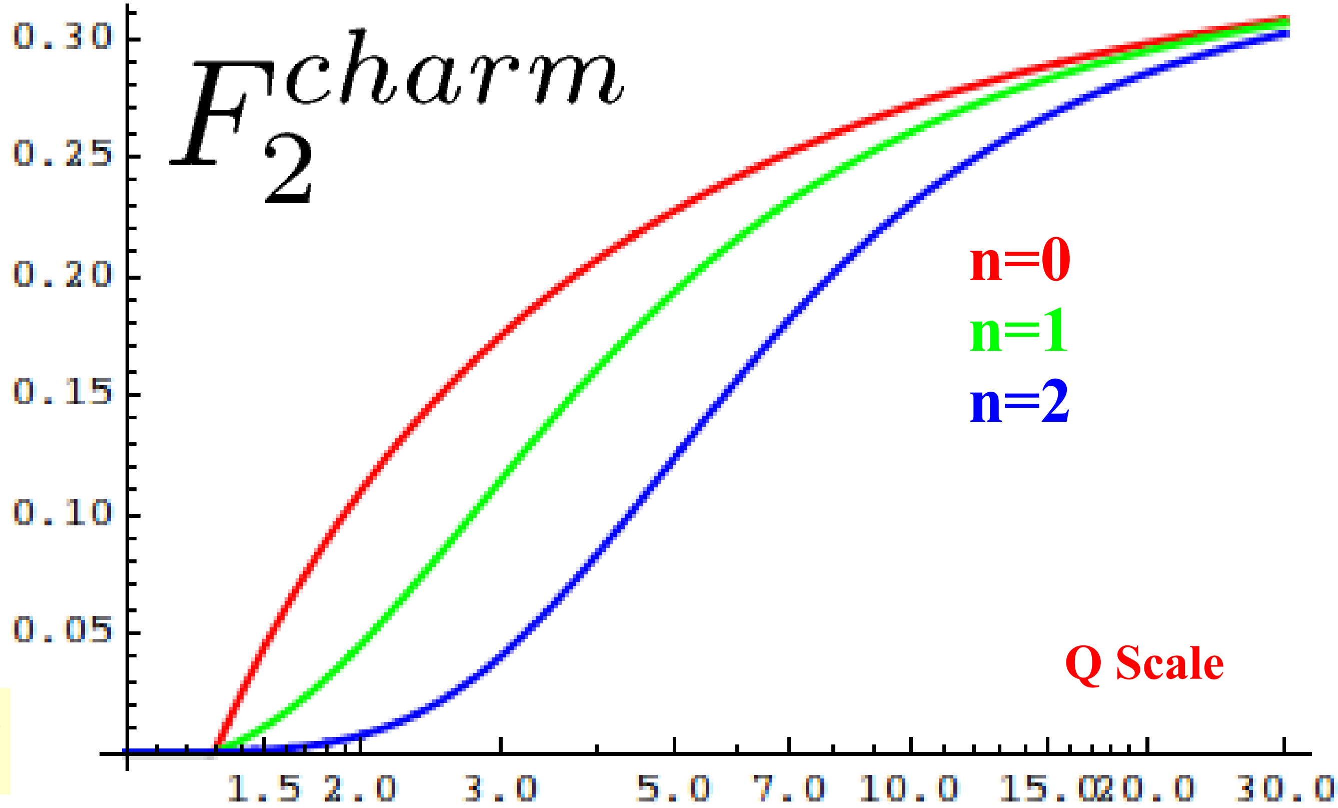
S-ACOT (Simplified-ACOT) ACOT with the initial-state heavy quark masses set to zero.
Phys.Rev.D62:096007,2000.

ACOT-χ & **S-ACOT-χ:** As above with a generalized slow-rescaling
Phys.Rev.D62:096007,2000.



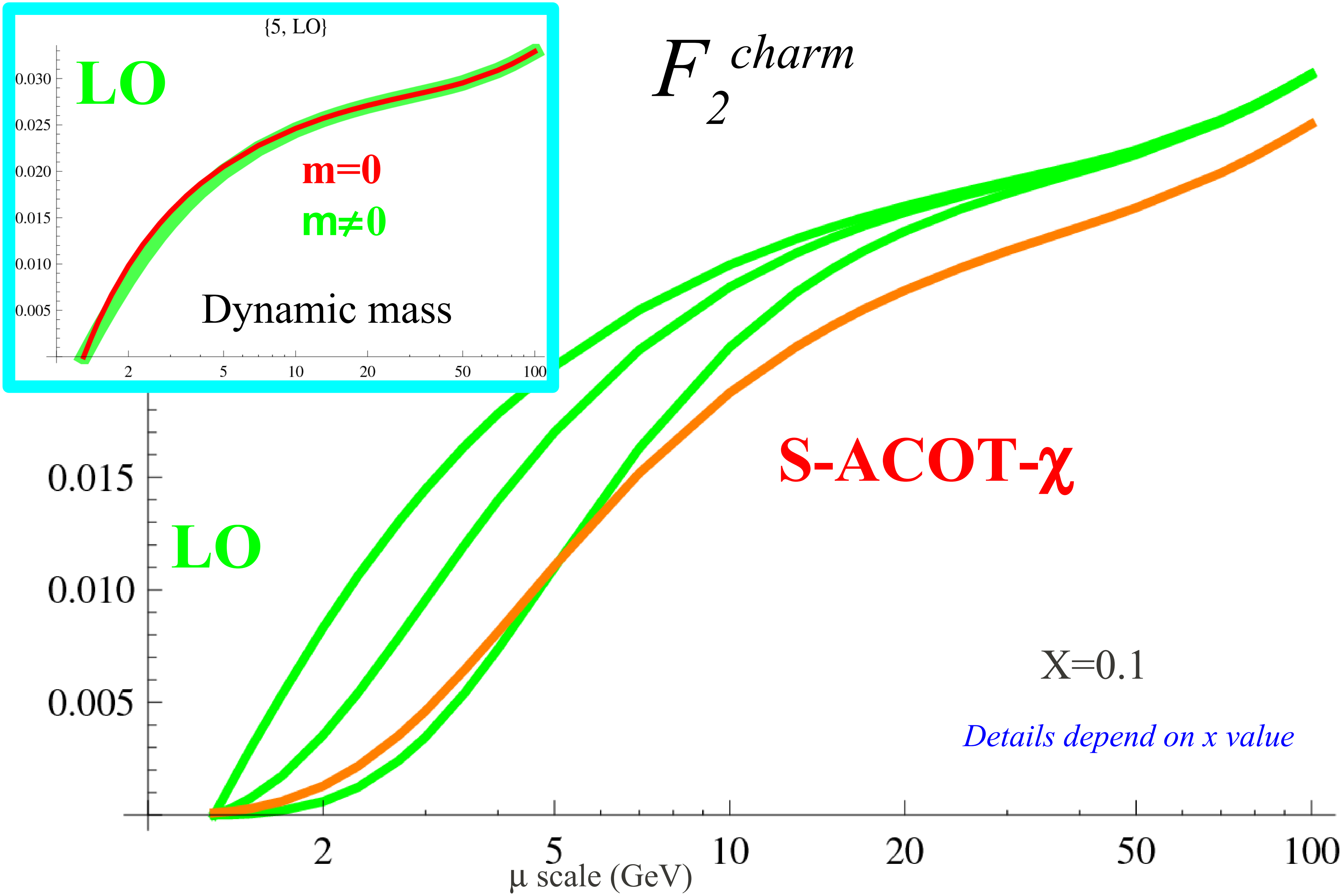
$$\chi = x\left[1 + \frac{(\mathbf{n}m_c)^2}{Q^2}\right]$$

Technically, violates factorization e.g., D-meson beam



Kinematic Masses are more important than Dynamical Masses *(in general)*

F_2 Charm in the threshold region



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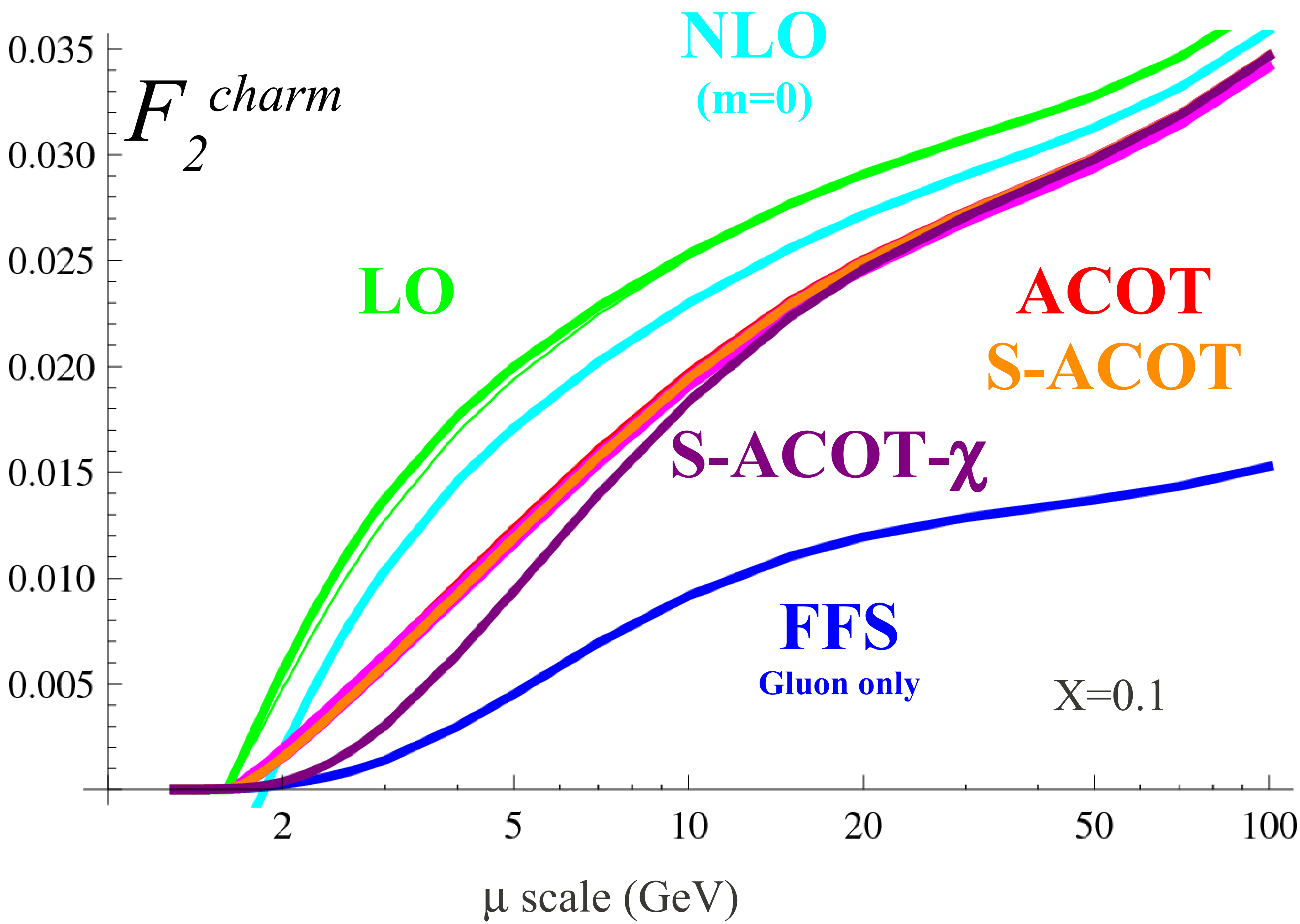
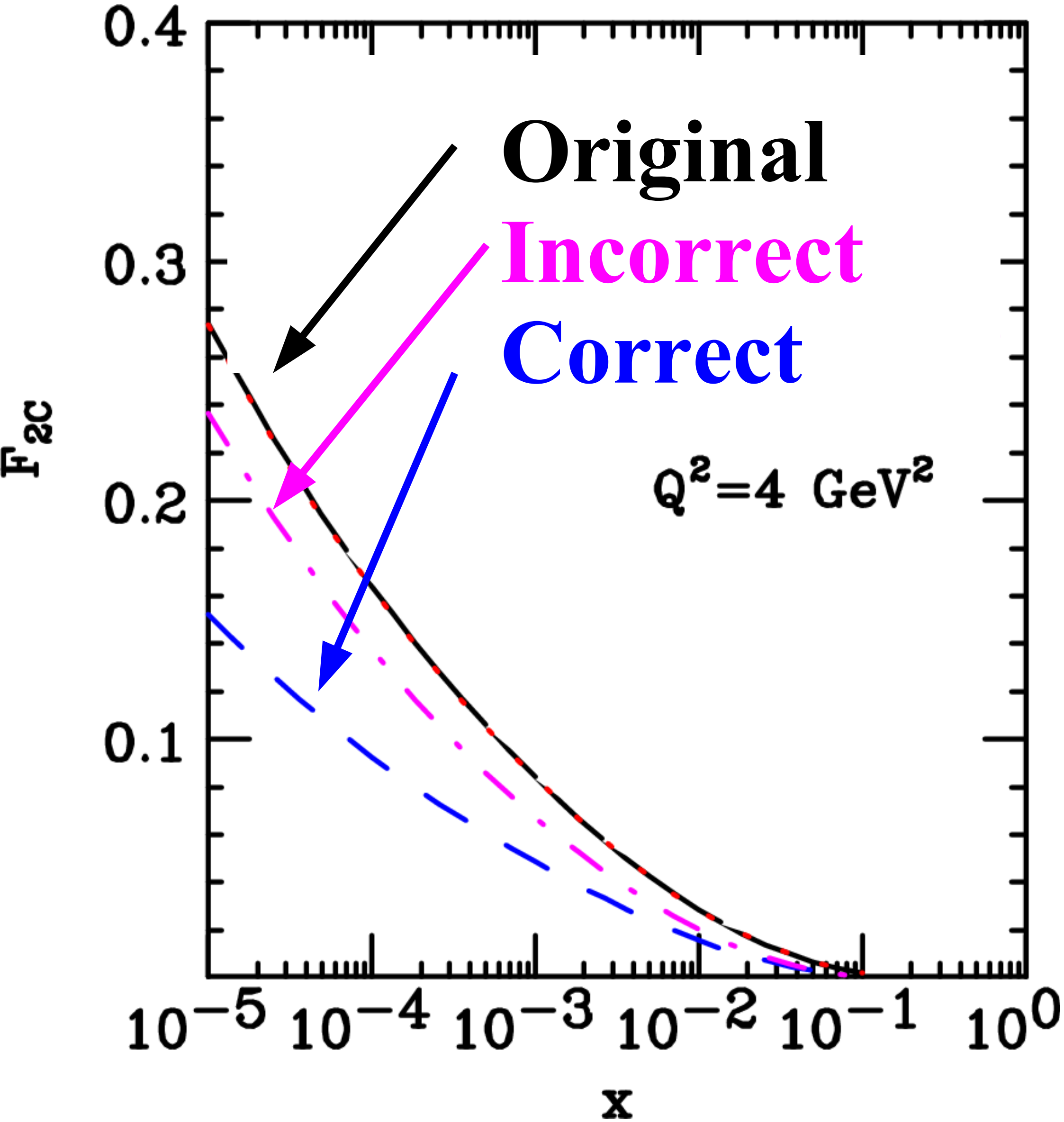


$F(\chi, Q)$???

Caution: Don't confuse $xF_2(x,Q^2)$ and $\chi F_2(\chi,Q^2)$



{x,Q} is correct kinematic point

Recall χ contains information of parton masses

schematically

$$F_2(x,Q) = x \int ...f(x)$$

$$F_2(\chi,Q) = \chi \int ...f(\chi)$$

$$F_2(x,Q) = x \int ...f(x)...\delta(x-\chi)$$

NNLO

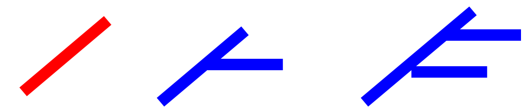
Application of Factorization Formula at Next to Next to Leading Order NNLO

Basic Factorization Formula

$$\sigma = f \otimes \omega \otimes d + \mathcal{O}(\Lambda^2/Q^2)$$

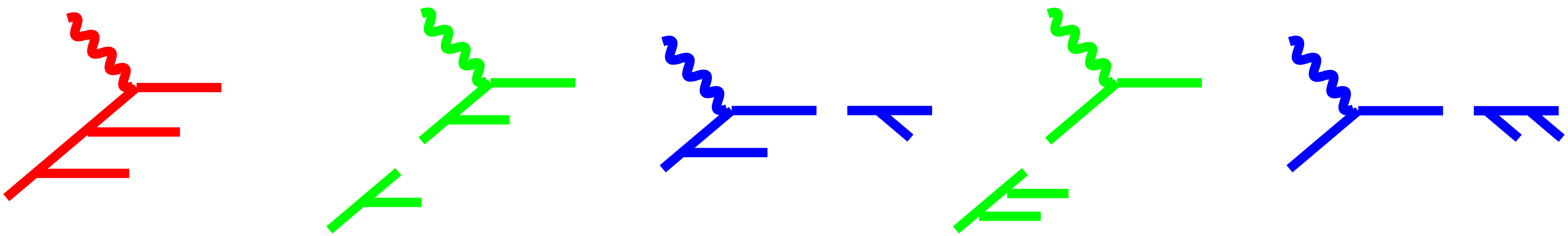
At NNLO:

$$\sigma^2 = f^2 \otimes \omega^0 \otimes d^0 + f^0 \otimes \omega^2 \otimes d^0 + f^0 \otimes \omega^0 \otimes d^2$$
$$+ f^1 \otimes \omega^1 \otimes d^0 + f^1 \otimes \omega^0 \otimes d^1 + f^0 \otimes \omega^1 \otimes d^1$$



f^0 f^1 f^2

We used: $f^0 = \delta$ and $d^0 = \delta$ for a parton target.



σ^2 $f^1 \otimes \sigma^1$ $\sigma^1 \otimes d^1$ $f^2 \otimes \sigma^0$ $\sigma^0 \otimes d^2$

S-ACOT:

Works great at NLO

Issues at NNLO

χ scaling:

Difficulties at NNLO

Issues ***even*** at NLO,

I showed you best case (x=0.1)

In contrast, full ACOT:

- Extensible to all orders

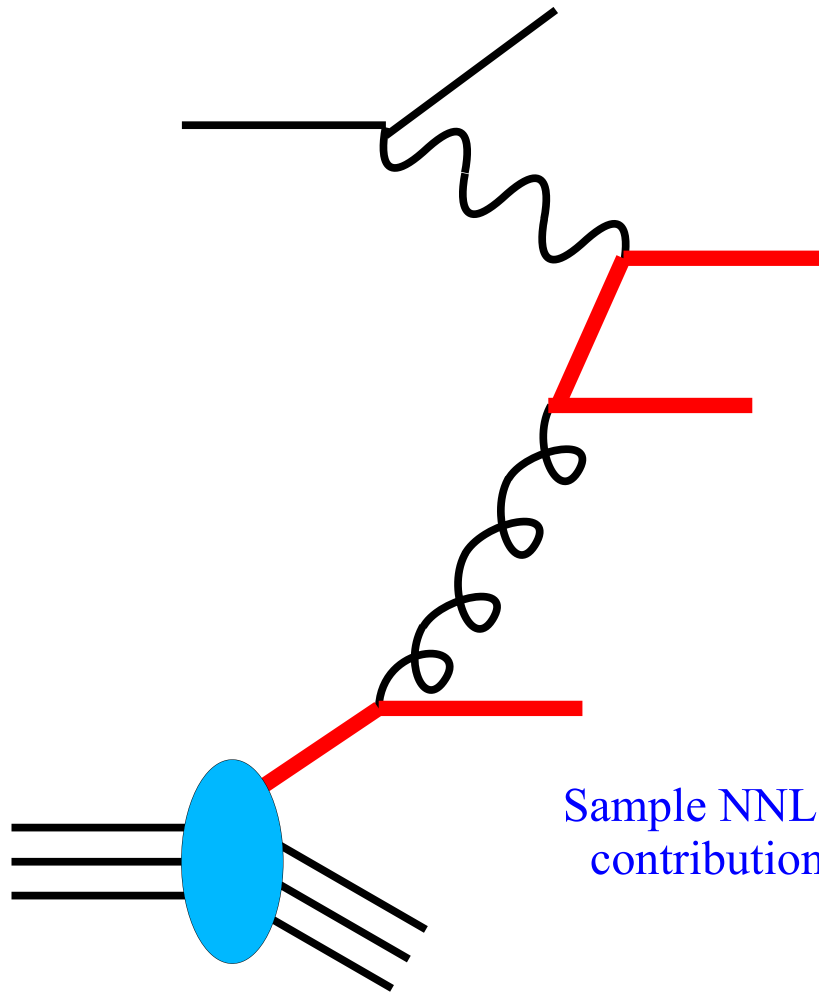
  Benefits from recent progress of higher order massive calculations

- Includes masses in scaling variable (χ)

  Avoids m ambiguities at NNLO

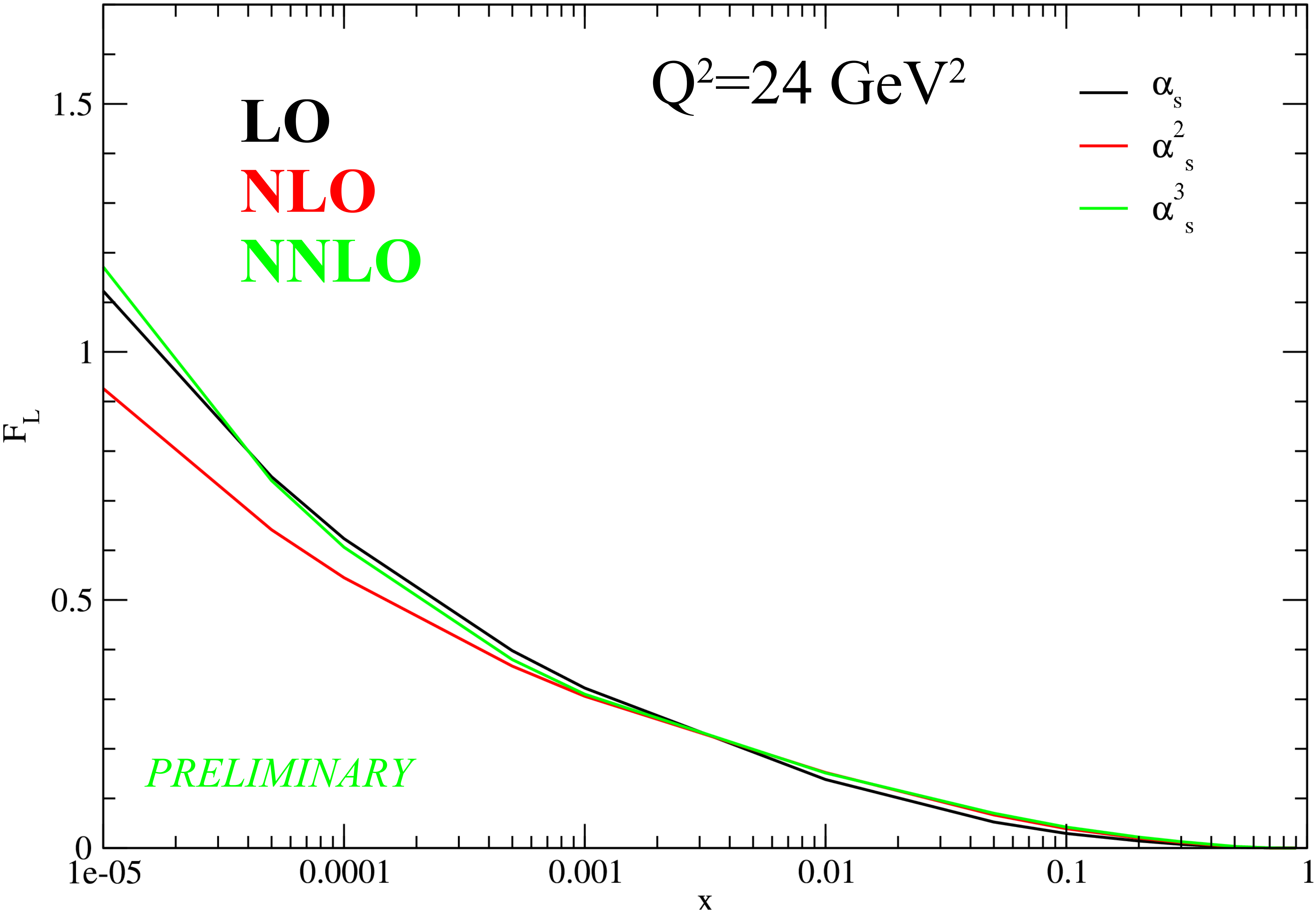
- Reduces to MS-Bar in $m \rightarrow 0$ limit

  No finite renormalization terms



Sample NNLO contribution

Preliminary: ACOT at NNLO



Conclusions

Heavy Quarks:

- Essential to properly incorporate mass effects for required precision
- Improved measurements of F^2, F^{cc}, F^{bb}, and F_L:
- Improved precision for LHC where heavy flavors play a prominent role

2009 Les Houches Benchmark Comparisons:

- Highlights recent progress
- Important reference point
- Shows theoretical scheme uncertainty
- Comparisons enlightening

Theoretically, we can now compute full dynamic mass range $[10^{-150}, 10^{+150}]$

- ACOT natural massive extension of MS-bar
- Separate roles of dynamic and kinematic masses illustrated
- Mass effects are essential:

Improvement, progresss, & understanding on theoretical side:

Thanks to: P. Nadolsky, K. Park, M. Guzzi I Schienbein, J.-Y. Yu, K. Kovarik, T.P. Stavreva
J. Owens, J. Morfin, C. Keppel, D. Soper …
& the Les Houches Working Group